

Enhanced microwave transmission through quasicrystal hole arrays

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We report on the observation of enhanced microwave transmission through quasi-periodic hole arrays in metal films. The fraction of transmitted light reaches 50% in a self-standing metal film and approaches 90% when the film is sandwiched between thin dielectric slabs, while the holes occupy only 10% of the sample area. The maximum transmission is accompanied by zero phase change, rendering the film almost 'invisible' over a wide frequency range. The extraordinary transmission phenomenon is interpreted in terms of resonances in the self-consistent interaction between holes, which are represented by effective electric and magnetic dipoles.

Little hope of having large light transmission through small subwavelength apertures was allowed by the pioneering work of Bethe, who predicted a drop in the intensity transmitted through a single hole of radius r in a thin perfect-conductor screen as $(r/\lambda)^4$ for large wavelength $\lambda \gg r$ [1]. However, the situation changed drastically when periodic arrays of apertures were considered rather than isolated holes. Although hole arrays have been extensively studied as artificial dielectrics in the past [2], the interest in this phenomenon was recently renewed by the work of Ebbesen et al [3], who demonstrated experimentally that the optical transmission through subwavelength hole arrays on metal films exceeds by several orders of magnitude the original predictions by Bethe. Initially, the enhanced transmission phenomenon was attributed to the excitation of surface plasmons on the metal film surfaces [4, 5, 6], at variance with a dynamical diffraction interpretation in that does not invoke plasmons and predicts the same effect in perfect conductors [7, 8]. In fact, the same effect was observed at THz [9, 10, 11] and GHz [12, 13, 14, 15] frequencies, followed by the subsequent identification of surface-bound modes in corrugated perfect conductors [16, 17], which play a similar role as plasmons in the optical domain. Although the periodic pattern of the structure was considered to be necessary to excite these surface modes, extraordinary transmission was observed also in quasi-periodic hole arrays in the optical regime [18, 19, 20, 21] and the origin of the phenomenon was traced back to the interaction of surface plasmons with Bragg peaks in the reciprocal space of the array [18, 21], whereas similar results were predicted also for perfect conductors [22].

It is known that a single hole on a thin [1] or a thick [23] metal film can be represented by a magnetic dipole parallel to the surface and an electric dipole perpendicular to it. In the case of a hole array, the collective response admits a representation in terms of the self-consistent po-

larization $\mathbf{p}_\mathbf{R}$ of each hole at the positions \mathbf{R} in response to an external field \mathbf{E}^{ext} plus the field induced by other holes $\mathbf{R}' \neq \mathbf{R}$ via the hole polarizability α , that is,

$$\mathbf{p}_\mathbf{R} = \alpha [E^{\text{ext}}(\mathbf{R}) + \sum_{\mathbf{R}' \neq \mathbf{R}} G(\mathbf{R} - \mathbf{R}') \mathbf{p}_{\mathbf{R}'}], \quad (1)$$

where $G(\mathbf{R} - \mathbf{R}')$ describes the field produced at hole \mathbf{R}

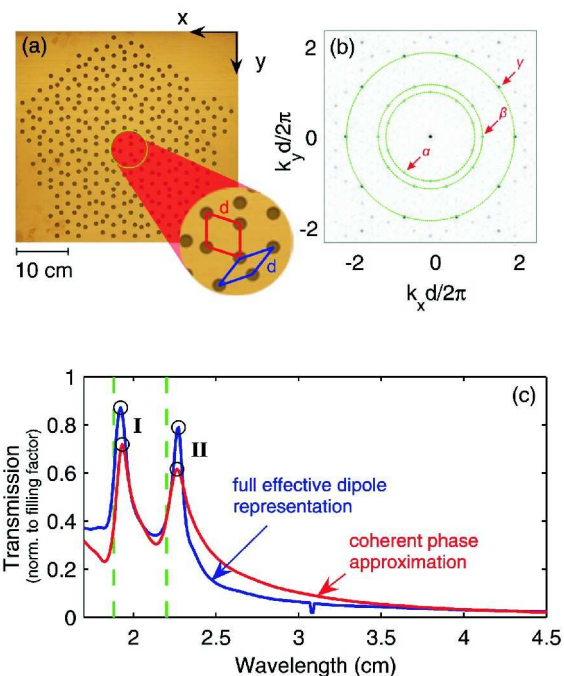


FIG. 1: Figure 1. (a) Quasi-periodic hole array drilled in a copper film deposited on a dielectric substrate. The basic units of the quasicrystal are two rhombi with side length d (inset). (b) Fourier transform of the quasi-periodic pattern normalized to d . The three strongest Fourier maxima (α , β , and γ) are contained in the corresponding green rings. (c) Normalized transmission of the hole array shown in (a), calculated in the full dipole representation of Eq. (1) (blue) and in the coherent phase approximation of Eqs. (2) & (3) (red). The dashed green lines mark the positions of the Wood's anomalies.

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by the polarization of the hole at \mathbf{R}' . In the small hole limit $\lambda \gg r$, we can retain only the dipolar component of \mathbf{p} [23]. By considering an incident plane wave with \mathbf{k}_{\parallel} momentum parallel to the film and assuming a $\exp(i\mathbf{k}_{\parallel} \cdot \mathbf{R})$ spatial dependence for the hole polarizability [24], Eq. (1) can be rewritten as

$$\mathbf{pR} \approx \frac{1}{\frac{1}{\alpha} - G_{\mathbf{k}_{\parallel}}} E^{\text{ext}}(\mathbf{R}), \quad (2)$$

where $G_{\mathbf{k}_{\parallel}} = \sum_{\mathbf{R}} G(\mathbf{R}) e^{-i\mathbf{k}_{\parallel} \cdot \mathbf{R}}$ is the sum of the dipole-dipole interaction over the quasi-lattice. Finally, the transmission T is given by the coherent superposition of the far field produced by all induced dipoles, or equivalently, the transmission along a direction defined by a projected parallel momentum $\mathbf{k}_{\parallel}^{\text{out}}$ is the far field produced by the dipole

$$\sum_{\mathbf{R}} \mathbf{pR} e^{-i\mathbf{k}_{\parallel}^{\text{out}} \cdot \mathbf{R}}. \quad (3)$$

The lattice sum $G_{\mathbf{k}_{\parallel}}$ exhibits pronounced maxima when the main diffraction peaks become grazing, which are the equivalent of the Wood anomaly condition in quasicrystal arrays. According to Eq. (2), the transmission will actually exhibit a minimum at the divergences of $G_{\mathbf{k}_{\parallel}}$ and a transmission maximum signaled by the minimum value of $|1/\alpha - G_{\mathbf{k}_{\parallel}}|$.

In order to further investigate the extraordinary transmission mechanism, we consider a quasi-periodic pattern consisting of 313 circular holes of radius $r = 0.46 \text{ cm}$. The side of the repeated basic units of the array is 2.31 cm (see Fig. 1a). In Fig. 1b, the reciprocal space of the quasicrystal is also shown, where it can be seen that it is composed by dense Bragg peaks and exhibits high orientational order. Although a very large number of peaks is visible, three very strong Fourier maxima can be distinguished (α , β , and γ), located at the circumference of circles with dimensionless radii equal to 1.05 (α), 1.23 (β), and 1.98 (γ), corresponding to spatial periods of 2.20 cm , 1.88 cm and 1.17 cm , respectively. The relation between the diffraction and transmission peaks becomes apparent in the calculated transmission spectra presented in Fig. 1c, using the coherent phase approximation (red) and the full solution of Eq. (1) (blue). Both calculations coincide reasonably justifying the coherent phase approximation. Moreover two transmission maxima are predicted at 1.92 cm (I) and 2.27 cm (II), corresponding to the two lowest frequency Fourier maxima of the quasicrystal (α and β).

The quasi-periodic pattern described above was used to manufacture two different samples of $44 \text{ cm} \times 46 \text{ cm}$ overall size, a self standing aluminium film of 0.5 mm thickness and a $35 \mu\text{m}$ copper film residing on a 1.5 mm thick dielectric substrate with permittivity $\epsilon = 3.77 + 0.03i$ (see Fig. 1a). The microwave measurements were performed in the range of 2 GHz to 18 GHz , in an anechoic chamber using a vector network analyzer and two

horn antennas. The sample was placed between the antennas and the transmitted intensity and phase at normal incidence were recorded.

The results for the polarization along the y-axis (see Fig. 1a) are shown in Fig. 2 and are normalized only to transmission through free space. For the orthogonal polarization similar (although not identical) results were obtained and are therefore omitted. In Fig. 2a, we present the data for the self-standing metal film. Two sharp transmissions peaks can be seen at 2.02 cm (I) and 2.34 cm (II) wavelengths on a slowly decaying transmission background. The magnitude of the peaks is 50% and 48% respectively, while at the same time the phase change of the transmitted wave for both peaks is close to zero. When the metal film is supported by a dielectric substrate (Fig. 2b), peaks I and II become considerably weaker (30% and 31%) and are separated by a point of zero transmission at 2.1 cm , where the phase is undefined. Moreover, a new transmission peak appears at 2.93 cm (III) (Fig. 2b). The magnitude of the new peak is approximately 65% and is accompanied by a zero phase change. If, in addition to the dielectric substrate, a superstrate of the same thickness and permittivity is introduced (Fig. 2c), peaks I and II are no longer visible. On the other hand, peak III increases in magnitude and reaches 90%, while the phase at the maximum is again zero. Moreover, peak III becomes broader and remains over 50% over a wide frequency range, from 7.5 GHz to 11 GHz .

In all cases, the transmission through the hole arrays exceeds Bethe's predictions, since about ~ 10 times more intensity than what is directly incident in the area occupied by holes is transmitted. The positions of the transmission peaks are dictated by the Fourier maxima of the quasi-periodic pattern and the presence of additional dielectric layers. In particular, for the case of the self standing array (Fig. 2a), the structure is symmetric and degenerate surface modes are excited along the two metal-air interfaces. The observed transmission peaks occur, as expected, very close to the positions predicted by the theoretical curves of Fig. 1a, while the peaks corresponding to shorter spatial frequencies (γ) are not observed, since they lie out of the measured frequency range. The more complicated spectral shape observed for the non-symmetric structure of Fig. 2b can be explained by taking into account the fact that the surface states on either side of the metal film are no longer degenerate. The transmission peaks (I, II) that originate from the metal-air interface are still visible, but they become considerably weaker. On the other hand, the dielectric-air interface leads to two new transmission peaks shifted to longer wavelengths. However, this frequency shift results also in an increase of the peak width and we believe that the two maxima partially overlap forming a very broad peak at $\sim 3 \text{ cm}$ (III). Furthermore, the confinement of the field near the metal surface becomes stronger and

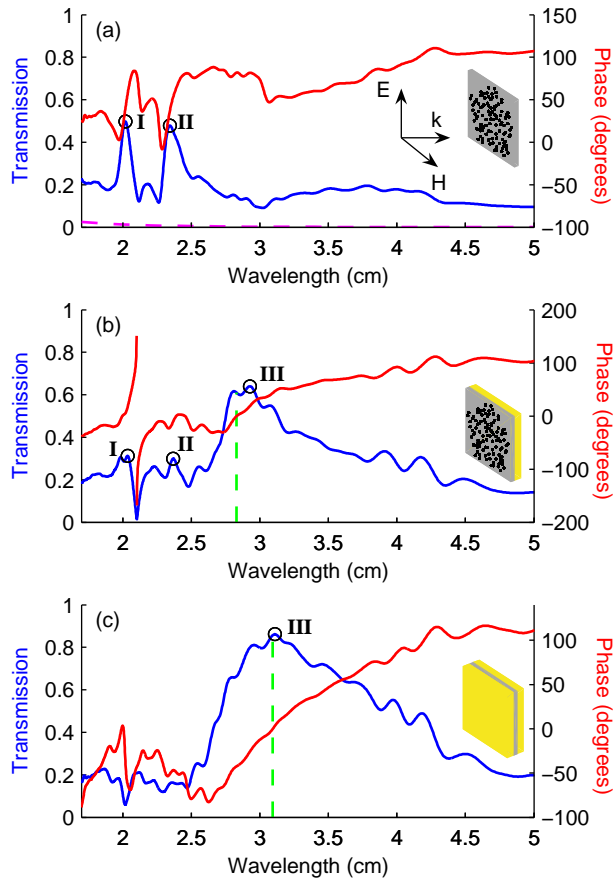


FIG. 2: Figure 2. Normal incidence transmission spectra through quasicrystal hole arrays on (a) a self-standing Al film, (b) a copper film supported by a dielectric substrate and (c) a copper film sandwiched between two identical dielectric slabs. The Bethe prediction is shown by the dashed purple line in (a), while the green lines in (b) and (c) mark the wavelength positions of "invisible metal" states, where high transmission is accompanied by zero phase change.

maximum transmission increases to 65%, while the corresponding phase change is zero, meaning that the incident wave remains almost unaffected as it propagates through the structure. Moreover, the phase singularity observed in between peaks I & II, could be attributed to the existence of Wood's anomalies in the metal-dielectric interface, although further investigation is required. When the degeneracy of the surface states is restored by adding a superstrate, only the joint peak (III) survives, while at the maximum the 90% transmission and the zero phase change render the structure virtually "invisible".

In conclusion, we have demonstrated, theoretically and experimentally, enhanced transmission of microwaves through quasi-periodic hole arrays in perfect conductors which can not support surface plasmons and a direct rela-

tion between the reciprocal space maxima and the transmission peaks was established. In particular, an "invisible metal" state has been observed, where almost total transmission with zero phase change can be achieved by placing a structured film between two dielectric slabs. The wavelength position of the total transmission can be tuned either by varying the permittivity of the dielectric slabs or by appropriately scaling the pattern. In fact, we have already shown that this design is widely scalable and exhibits extraordinary transmission down to the telecom spectral region [19, 20]. Furthermore, the results presented here are almost independent of the polarization of the incident wave, due to the high orientational order of the quasicrystal. These characteristics are much desired in practical applications and we expect that such structures can prove useful over a wide region of the electromagnetic spectrum.

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